N72-23098

A STUDY OF ALTERNATIVE METHODS FOR RECLAIMING OXYGEN FROM CARBON DIOXIDE AND WATER BY A SOLID-ELECTROLYTE PROCESS FOR SPACECRAFT APPLICATIONS

Final Report for Task I of Contract NASw-2286

Prepared by
The Bioenvironmental Systems Advisory Committee
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For
National Aeronautics and Space Administration
Washington, D.C.

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1. INTRODUCTION

1.1 BACKGROUND

The Society of Automotive Engineers, Inc., has been requested by the National Aeronautics and Space Administration, Headquarters, on Contract No. NASw-2286, to organize a Bioenvironmental Systems Advisory Committee to counsel NASA on specific technical matters relating to life-support systems for spacecraft. This report documents the results of a study performed by the Committee on the first task of the contract. The purpose of the study, as specified in the contract work statement, was to review technical work accomplished to date by two NASA contractors, Applied Electrochemistry Inc. and Westinghouse Electric Corporation, on methods to reclaim oxygen from carbon dioxide and water by an electrochemical process using a solid-electrolyte cell. Based upon this review, recommendations were to be formulated by the Committee to counsel NASA on (1) the advisability of moving rapidly into engineering prototype development and fabrication of a full-scale model for this system concept, based upon progress to date; (2) the optimum choice of method or approach to be carried into engineering prototype development; and (3) the technical problem areas which now exist and which should be resolved during the next phase of work, with any specific technical improvements which the Committee can suggest.

For the past several years NASA has sponsored research on the application of an electrochemical process using a solid-oxide electrolyte (zirconia stabilized by yttria or scandia) for oxygen reclamation from carbon dioxide and water, for spacecraft life-support systems. During the initial phases of work (to date), two alternative technical approaches for such a process have been investigated by two contractors: Applied Electrochemistry Inc. in Mountain View, California, and Westinghouse Electric Corporation in Pittsburgh, Pennsylvania. NASA has determined that this year it must decide if progress to date on these studies warrants proceeding to the production of an engineering prototype. In addition, NASA plans to select one contractor, having the best chance of success, to undertake this next phase of the program. To support this decision process, NASA determined that a qualified, competent and unbiased group should perform a critical review and assessment of the scientific and technological progress on each of the contracts, and report its findings and recommendations to NASA.

A committee of experts in the interrelated fields of electrochemistry, chemical process engineering, and spacecraft life-support systems engineering was selected by the Society of Automotive Engineers and given the responsibility to accomplish this study. The members of the Committee were:

Dr. Jack M. Spurlock
Health and Safety Research Institute
(Committee Chairman)

Dr. H. P. Meissner
Massachusetts Institute of Technology

Dr. Elton J. Cairns
Argonne National Laboratory

Dr. Douglas N. Bennion
University of California at Los Angeles

Dr. G. H. Beyer
Virginia Polytechnic Institute and State University

Career resumes for these committee members are included in Appendix I of this report.

1.2 METHOD OF PROCEDURE

The Committee accomplished its assigned task by convening a series of meetings in which the Committee was either briefed by NASA and contractor representatives or it deliberated the problem privately. During the first of these sessions, the Committee met for an entire day with NASA technical representatives from NASA Ames Research Center and NASA Langley Research Center, sponsors of the research and development work on electrochemical oxygen recovery from CO_2, to receive thorough briefings on efforts to date on the two programs, and reports on the current status of the programs. During the second session, the Committee held a half-day meeting with representatives of Applied Electrochemistry Inc. (AEI), at their facility in Mountain View, California, and was briefed on AEI's technical approach, steps in fabrication and testing, test results to date, and systems planning. During the third session, the Committee held a half-day meeting with representatives of Westinghouse Electric Corporation at their facility in Pittsburgh, Pennsylvania, for the same type of briefing. At these meetings with the contractors' representatives, the Committee members discussed the technical factors with these representatives, in great detail, to elucidate the factors involved, the state of the technology, and prospects for the success of an engineering prototype development program.

During the remaining sessions, the Committee reviewed thoroughly the information it had received, Contractors' reports and proposals, and all other pertinent aspects of the matter. The options to NASA were deliberated fully and recommendations were formulated. Associated with this analysis of the matter was a fundamental rationale which eventually formed the basis for the Committee's conclusions and recommendations. This rationale, including the analysis of the information provided to the Committee and the resultant assessment of the decision alternatives, is presented in Section 2 of this report. The Committee's conclusions and recommendations are summarized in Section 3.

2. ANALYSIS AND RATIONALE

This section of the Committee's report reviews the principal factors involved in: the Committee's analysis of the present status of the two alternative methods for oxygen reclamation from carbon dioxide and water by an electrochemical process using a stabilized zirconia electrolyte; an assessment of relative position with respect to readiness and promise for successful engineering prototype development; and the Committee's rationale for the conclusions and recommendations presented in Section 3.

2.1 ANALYSIS OF PERTINENT FACTS

Based upon the briefings provided to the Committee by the NASA representatives and the contractors' representatives (from Applied Electrochemistry Inc. and Westinghouse Electric Corporation), visits by the Committee to the contractors' laboratories, and a review of available reports, etc., prepared by the contractors on their respective NASA projects, the Committee conducted an analysis of the relative team capabilities, technical features of their work to date, relative key strengths and weaknesses with respect to potential for achieving required objectives in the production of an engineering prototype system, and other pertinent factors for comparison. The major results derived from this analysis are summarized below.

2.1.1 Applied Electrochemistry Inc. (AEI)

The commendable competency of the AEI team and its management is reflected by the high quality of the electrolyte material, which they compound themselves, and the brazing and sealing techniques which they have developed. The emphasis of their efforts to date has been on electrochemical cell fabrication and development. Relatively little effort has been devoted to development of systems components outside the cell. The key strengths and weaknesses as they relate to the problem of concern to the Committee can be summarized as follows:

A. Strengths:

1. High-quality sealing technology.
2. High-quality electrolyte formulation and fabrication technology.

3. Excellent quality control in cell fabrication and assembly, resulting in a high-quality product.
4. Success in producing a very high-quality (high purity) oxygen product for up to 126 days.

B. Weaknesses:

1. Lack of engineering experience and team capability in process and equipment engineering.
2. Credible potential for engineering success in operation of their concept as a system has not been demonstrated.
3. Lack of adequate systems engineering awareness and capability. For example, a more complex flow sheet results from the plan to electrolyze water separate from CO_2, rather than simultaneously in the same cells.
4. Electrodes appear to be relatively vulnerable to degradation from higher current-density operation.
5. Inadequate attention has been given to understanding certain mass and heat transfer processes in the cell, particularly in the electrode; analysis of these processes could serve as a basis for cell improvement.

2.1.2 Westinghouse Electric Corporation

The overall team capability and availability of talent within the Westinghouse research and development operation includes excellent engineering and systems engineering experience. Appreciation of the problems associated with systems design and the need for careful attention to systems engineering considerations has led to an early demonstration of an operating "breadboard" system. This system was sufficiently successful that it provides a reasonable basis for engineering prototype development. The concept of using electrolyte particles as part of the electrode structure enhances mass transport processes in the electrode and appears to have distinct advantages in increasing electrode performance and life. The key strengths and weaknesses as they relate to the problem of concern to the Committee can be summarized as follows:

A. Strengths:

1. Adequate engineering and systems engineering capability and awareness.
2. Demonstration of good long-life electrodes at acceptable current densities.

3. Demonstration of an operating system with acceptable performance over a 180-day period.
4. Simplification of flow sheet resulting from simultaneous electrolysis of CO_2 and water.

B. <u>Weaknesses</u>:

1. Questionable adequacy of the cell sealing techniques used to date.
2. Relatively high CO_2 content in the product oxygen stream.
3. High CO_2 concentration in the product stream suggests the possibility of an inherent degradation process that can occur during the operation of the system; this may stem from sealing problems.
4. Inadequate attention has been given to understanding certain mass and heat transfer processes in the cell, particularly in the electrode; analysis of these processes could serve as a basis for cell improvement.

2.1.3 General Comparison

By way of summary, the two process approaches can be compared on the basis of the respective key strengths and weaknesses of the contractors in this field of technology, and the apparent potential effect of these strengths and weaknesses on engineering prototype system development for the solid-electrolyte process. This comparison, by major technical groupings, is presented below.

A. Neither group has conducted adequate basic analyses of mass transport to and in the porous electrode and the relationship of CO concentration in the electrode to electrode failure, and its effect on electrode performance. Similarly, neither group has performed overall heat-transfer engineering analyses and heat balances to serve as a basis for energy management (especially the distribution of heat to maintain proper temperature distribution within the system), design of controlled heat leaks, etc. This, then, is a fundamental weakness shared rather equally by the two contractor teams, but it has not seriously limited technical progress to date. It should, however, be a factor of concern during the prototype development phase.

B. It appears that Westinghouse has demonstrated a clear advantage by successfully operating a breadboard system for 180 days, experiencing no serious problems that would prevent them from proceeding logically to the next step of engineering prototype system development. This presumes that the lower quality (higher CO_2 concentration) of the product oxygen stream of the Westinghouse system is compatible with the total system and mission requirements anticipated by NASA. In particular, this assumes that it is convenient and acceptable to impose the additional (small) duty load on the CO_2 scrubber in the life-support system, and to process the product oxygen stream through a system such as a trace-contaminant control unit before it is used for oxygen makeup in the cabin atmosphere. Westinghouse appears to have the team capability to undertake the engineering prototype development effort. The Committee regards these as key advantages and key considerations in the decision process.

C. The fact that Westinghouse has demonstrated this readiness advantage does not at all mean that additional improvements in system and component technology are not appropriate or desirable. In fact, a careful optimization analysis should be performed to determine the value of additional efforts to improve electrolyte material selection, sealing, etc. For example, there is a possibility that the electrolyte material developed by AEI could prove advantageous if used in the Westinghouse device.

D. The basic geometries were also compared by the Committee to identify any relative advantages regarding sealing requirements or problems. Using data from the most recent AEI and Westinghouse reports, and summary sheets provided by NASA, it was calculated that the Westinghouse units require 0.615 cm of seal length per sq cm of active anode area, compared with 0.795 cm of seal length per sq cm for the AEI configuration. Similarly, in terms of number of seals required, there are 0.178 seals per sq cm of active anode area for the Westinghouse configuration, compared with 0.156 seals per sq cm for the AEI configuration. In this respect, the two configurations are about equally complex; however, the Westinghouse design presently uses their porous electrodes as part of the seal, which suggests an inherent tendency toward leaks. This is an area for improvement in the Westinghouse design, unless stronger evidence can be presented to show that the potential-problem threat is not serious. Perhaps some of AEI's sealing technology could be transferred advantageously to improve the Westinghouse seals.

E. One of the key technical strengths of the Westinghouse approach is the method of construction of the porous electrodes. The Westinghouse electrodes appear to be more durable and to give better performance than the AEI electrodes. Westinghouse has demonstrated operation at 120 to 170 mA per sq cm for up to 8000 hours, and has reported that operation at 200 mA per sq cm should be possible with their present technology. In contrast, AEI has demonstrated operation at 100 mA per sq cm for 2,000 hours, and AEI's representatives feel that they may be able to reach 150 mA per sq cm, but that 200 mA per sq cm seems beyond the limits of their present technology. The increased current density of the Westinghouse unit should give it a clear advantage in oxygen production per unit weight or volume.

F. Representatives of both Westinghouse and AEI suggested that their respective configurations had the geometric advantage in terms of packing (or packaging) efficiency. The Committee's analysis indicated that Westinghouse has a modest advantage in terms of anode area per unit of cell volume. But AEI could probably offset this advantage by increasing the diameter of its drums or decreasing drum height, if AEI is not too heavily committed to the present drum configuration. In general, no clear advantage (or advantage potential) could be identified for either the Westinghouse or the AEI configuration.

2.2 DECISION ALTERNATIVES

The analysis summarized above rather clearly suggests that the Westinghouse technical approach to the system has key net advantages over the AEI approach, and that the Westinghouse team also shows better potential for success in an engineering prototype development effort. AEI still faces several unresolved problems which are potentially significant threats to successful system operation and demonstration. Given enough time and money, perhaps these problems could be solved. But the problems remaining to be solved by Westinghouse do not appear to pose enough of a threat to success (within the conditions and assumptions stated in 2.1.3B, above), nor are the potential advantages offered by the AEI approach attractive enough to justify a delay in proceeding with engineering prototype development for the Westinghouse approach. Beyond a decision to proceed with this approach, there are several decision alternatives, all involving engineering prototype development of the Westinghouse approach, from which a procedure that would best satisfy NASA's overall objectives, within usual constraints, can be selected. These alternatives or options and their relative advantages and disadvantages, are summarized below.

2.2.1 Option I - Engineering Prototype Development Only

This would involve proceeding with engineering prototype development of the Westinghouse approach without further research efforts to improve electrolyte materials, the sealing technique, or other technical aspects of the solid-electrolyte system which could potentially improve performance and reliability (especially the quality of the product oxygen stream). This would rely upon the adequacy of the present configurations for major components, and accept the presently obtainable quality of the product oxygen stream from the Westinghouse process. The key advantage is a possible reduction in program cost by not funding a parallel research study to seek improvements in technology. However, the key disadvantage is the relatively high risk which the Committee estimates is involved in relying upon the Westinghouse system in its present state. The Committee believes that there is possibly an inherent weakness in the present sealing technique which may account for the high CO_2 content in the product stream, and which could lead to performance degradation during long-term use of the system (even though this did not appear to occur in the 180-day tests). Therefore, the disadvantage of choosing this option is that backup technology would not be available, in a timely manner, to provide improvements should the development program reveal such shortcomings in the present configuration.

2.2.2 Option II - Engineering Prototype Development with Parallel Research Efforts

This alternative would involve proceeding essentially simultaneously with engineering prototype development of the Westinghouse approach and parallel continuation of research to seek improvements in components, materials, sealing and other aspects of solid-electrolyte technology. This would assume that such parallel research efforts are justified and presently offer significant promise of eventually benefiting the development program. The key advantage is the lowering of the risk, or improving the chances of success in developing a high-performance, reliable system. The disadvantages are the additional cost required to carry on the parallel research effort, and the fact that this research effort <u>does not guarantee</u> that significant improvements in system performance and reliability will result.

2.2.3 Option III - Engineering Prototype Development with a Preliminary Benefit Study before Deciding upon a Parallel Research Effort

This alternative would involve proceeding with the engineering prototype development of the Westinghouse approach and, in parallel, starting a relatively short program to study the potential benefits that might be derived from a parallel research program, including a good tradeoff study based upon existing information from both the AEI and the Westinghouse programs. The advantage is a careful review of the cost-effectiveness of a parallel (and possibly costly) research effort before a decision is made to proceed with such an effort. The disadvantage would be the additional cost of the benefit-analysis study should it be determined that the parallel research program is, after all, a worthwhile investment for NASA.

2.3 SOME GENERAL MANAGEMENT OBSERVATIONS

2.3.1 Selection Among the Three Options

The Committee has tried to realistically characterize the key advantages and disadvantages of the three options summarized above in Sections 2.2.1, 2.2.2 and 2.2.3. The management decision process for choosing among these three options reduces to risk-versus-cost considerations. It appears that the least risk is provided by Option III, but it would likely lead to the highest overall cost should the parallel research program eventually be funded. Nevertheless, the additional cost of the benefit-analysis study should not be very big compared with forecast values of overall program costs for research and development of the solid-electrolyte system for spacecraft applications. Similarly, although Option I offers a potential cost savings, it is attended by a significant risk that the backup research may be required in the long run, after all, and the development program would then be delayed until such research results could be produced.

2.3.2 Review Procedures

Should NASA choose either Option II or Option III, it will be necessary to assure that the parallel research program or the benefit analysis are conducted effectively. This means that study objectives should be clearly stated in the work statement, the proposed plan of accomplishing these objectives should be carefully reviewed by NASA, and actual procedures and results should be reviewed frequently during the course of the study to assure that potential improvements are recognized and given thorough consideration. The Committee was quite concerned that during the discussions with the Westinghouse team, the Westinghouse representatives were rather reluctant to admit (or could not recognize) that their choice of materials, their sealing techniques, and other features of their system, could possibly be improved and thereby improve reliability and performance characteristics for the system. Yet, they could not substantiate their opinions with clear evidence of a credible tradeoff analysis. The Westinghouse position may be a result of their concentration, to date, on achieving a system design and demonstration as fast as possible, and from NASA's emphasis on this approach. Perhaps, also, they believed that admitting possible areas for improvement would weaken their readiness impression on the Committee. Whatever the reason, NASA must provide close guidance, counsel and encouragement and emphasize the importance of good performance on the research or benefit-analysis tasks. If the Westinghouse team cannot, in fact, recognize areas in which research to seek improvements, or potential sources of benefit, is worth consideration, then NASA must provide strong technical guidance along the lines mentioned earlier in this report. If, however, the Westinghouse team can recognize these areas but has not given serious consideration to such research because of NASA's emphasis on systems design, then NASA must seek to compensate for this emphasis through encouragement of the research or benefit-analysis efforts.

2.3.3 Prognosis

In recommending that NASA select Westinghouse to conduct the engineering prototype development program, the Committee believes that Westinghouse can proceed more rapidly with the engineering, and that their design itself is the more readily scalable. The question of whether the device will pass the further tests in its development, such as vibration tests and restart tests, remains unanswered. The Committee is generally optimistic about chances of success, but it must base this optimistic prognosis on the available results, which do not include conclusive evaluational data or trends for several key performance factors. Hopefully, these questionable design factors will be resolved early in the prototype development program.

3. CONCLUSIONS AND RECOMMENDATIONS

Based upon the material presented in Sections 1 and 2 of this report, some key conclusions and recommendations have been formulated. These are summarized below.

1. The Westinghouse approach to the system has key net advantages over the Applied Electrochemistry Inc. approach, and the Westinghouse team also shows better potential for success in an engineering prototype development effort.
2. The relatively low quality (high CO_2 content) of the product oxygen from the Westinghouse system suggests the possibility of an inherent weakness in the present sealing technique which could lead to performance degradation during long-term use of the system (although this did not occur in the 180-day tests). This should be given serious attention.
3. Of the three options identified by the Committee as decision alternatives for NASA (presented in Section 2.2), the most promising appears to be Option III - "Engineering Prototype Development with a Preliminary Benefit Study Before Deciding upon a Parallel Research Effort." In any event, consideration of a parallel research effort appears to be very important to the improvement of the probability of success on the engineering prototype development effort.
4. It is recommended that NASA closely monitor efforts on any parallel research program, or the benefit analysis study that would evaluate the need for such a program, to assure that these are conducted effectively. Present potential problem areas associated with the Westinghouse system should be assessed carefully and realistically.

5. The following specific areas of improvement or attention are recommended as subjects of a parallel research program:

   - ° Improved sealing technique to give strength and long-term reliability.
   - ° Improved electrolyte performance through the use of a better electrolyte material (with a cost-benefit analysis).
   - ° Improved method of preparing and applying the electrodes to assure uniformity.
   - ° Analysis of mass transport to and in the porous electrodes to serve as a guide to cell improvements.
   - ° Overall heat-transfer engineering analysis to serve as a basis for optimum energy management.

APPENDIX I

CAREER RESUMES FOR COMMITTEE MEMBERS

A. Dr. Jack M. Spurlock
B. Dr. H. P. Meissner
C. Dr. Elton J. Cairns
D. Dr. Douglas N. Bennion
E. Dr. G. H. Beyer

A. BIOGRAPHICAL DATA FOR DR. JACK M. SPURLOCK

Education: B.S., Chemical Engineering, University of Florida, 1952
M.S., Chemical Engineering, Georgia Institute of Technology, 1958
Ph.D., Georgia Institute of Technology, 1961.

Experience:

Theodore Jonas and Associates -- Systems engineering and government relations consultant, 1971 to date.

Health and Safety Research Institute -- Executive Vice President and Director of Research, 1969-1971.

Atlantic Research Corporation -- Director of the Engineering Research Department, 1964-1969.

Martin Marietta Corporation -- Manager of the Aerosciences Research Department, 1962-1964.

University of Florida -- Adjunct Professor of Engineering, 1963-1964.

Georgia Institute of Technology -- Research Associate and Assistant Professor, School of Chemical Engineering and Engineering Experiment Station, 1955-1962.

Auto-Lite Battery Company -- Process and Quality Control Engineer, 1954-1955.

Professional Activities:

Chairman of Environmental Control and Life Support Systems Committee (SC-9), Society of Automotive Engineers.

Newsletter Editor for Heat Transfer and Energy Conversion Division, American Institute of Chemical Engineers.

Fellow, American Institute of Chemists, and Professional Chemist - Accredited.

Associate Fellow, American Institute of Aeronautics and Astronautics.

Member of Sigma Xi.

Member of Aerospace Medical Association.

Member of American Association for the Advancement of Science.

Member of American Chemical Society.

Member of the Biomedical Engineering Society.

Member of Southern Medical Association.

Member of American Society for Engineering Education.

Member of the Association for the Advancement of Medical Instrumentation.

Guest lecturer for numerous university graduate seminars in systems engineering, biomedical and safety engineering, and environmental engineering, nationwide.

Publications:

Approximately 40 articles and reports in the fields of spacecraft systems engineering, aerospace safety, aerospace medicine, transport phenomena, environmental affects, combustion, and biomedical engineering.
Co-author, with Dr. T. W. Jackson, of a book "Research and Development Management", published by Dow Jones-Irwin.
Awarded patents for biomedical engineering devices.

B. BIOGRAPHICAL DATA FOR DR. HERMAN P. MEISSNER

Education:

B.S., Chemical Engineering, Massachusetts Institute of Technology, 1929
M.S., Chemical Engineering, Massachusetts Institute of Technology, 1930
Sc.D., Univ. of Frankfurt am Main, Germany, 1938

Experience:

Massachusetts Institute of Technology --

DuPont Fellow in Business and Engineering Administration,1932-33.
Instructor, Business and Engineering Administration, 1934-36.
Instructor, Chemical Engineering Department, 1938-40.
Asst. Prof., Chemical Engineering Department, 1940-43.
Assoc. Prof., Chemical Engineering Department, 1943-51.
Professor, Chemical Engineering Department, 1951 to date.
Executive Officer, Chemical Engineering Department, 1970 to date.
Lammot du Pont Professorship, 1970 to date.

Professional Activities:

Consultant, Chemical Corps, U. S. Army, 1950-55, Special Committee, Saline Water

Member of American Institute of Chemical Engineers

Member of American Chemical Society

Member of American Academy of Arts and Sciences

Member of Sigma Xi.

Publications:

Approximately 40 articles and numerous patents
Joint Author: "Advanced Thermodynamics for Chemical Engineers", 1958
Author: "Processes and Systems in Industrial Chemistry", 1970.

C. BIOGRAPHICAL DATA FOR DR. ELTON J. CAIRNS

Education: B.S., Chemical Engineering and Chemistry, Michigan Technological University, 1955
Ph.D., University of California (Berkeley), 1959

Experience:

Argonne National Laboratory -- Group Leader in the Chemical Engineering Division, 1966-1969.
Section Head, Energy Conversion Section, Chemical Engineering Division, 1969 to date.

General Electric Research Laboratory -- Research in electrochemistry and fuel cells, 1959-1966.

Professional Activities:

Member of Subpanel No. 4 of the Federal Electrically Powered Vehicles Panel, 1967.

Member of Program Evaluation Committee for the Office of Saline Water, U. S. Dept. of Interior, 1969.

Member of Energy Conversion Panel for Department of Defense, 1969 and 1970.

Member of U. S. Delegation to NATO meeting on air pollution in Eindhoven, 1971.

Invited speaker at Gordon Conferences on Fused Salt, 1967 and 1969.

Served as rapportuer for the Intersociety Energy Conversion Engineering Conference; currently a member of Steering Committee.

Editor of Journal of the Electrochemical Society (recipient of their Francis Milles Turner Award, 1963).

Member of Palladium Medal Award Committee and Publication Committee of the Electrochemical Society.

Member of CITCE

Member of American Chemical Society

Fellow of American Institute of Chemists

Member of Executive Committee of the Heat Transfer and Energy Conversion Division, Chairman of Energy Conversion Committee, and Member of National Program Committee, American Institute of Chemical Engineers.

Member of New York Academy of Sciences.

Publications:

Over sixty articles in the fields of electrochemical kinetics, fused salts, thermodynamics, surface chemistry, catalysis, transport phenomena, and lithium/chalcogen cells.
Co-author (with Dr. H. A. Liebhafsky) of a book "Fuel Cells and Fuel Batteries."

D. BIOGRAPHICAL DATA FOR DR. DOUGLAS N. BENNION

Education: B.S., Chemical Engineering, Oregon State University, 1957
Ph.D., University of California (Berkeley), 1964

Experience:

University of California, Los Angeles -- Associate Professor of Engineering, Energy and Kinetics Department, School of Engineering and Applied Science, 1964 to date.

Industrial Consulting -- consultant in development of new batteries, reverse-osmosis technology and corrosion problems, 1966-1970.

Dow Chemical Company -- Chemical Engineer, 1957-1960.

Professional Activities:

Registered Professional Engineer, State of California.

Member of The Electrochemical Society.

Member of American Institute of Chemical Engineers.

Publications:

Over fifteen articles in the fields of electrochemistry, membrane transport processes and thermophysical property measurements.

E. BIOGRAPHICAL DATA FOR DR. GERHARD H. BEYER

Education: B.S., Chemical Engineering, University of Wisconsin, 1944
M.S., Chemical Engineering, University of Wisconsin, 1947
Ph.D., University of Wisconsin, 1949

Experience:

Virginia Polytechnic Institute and State University -- Professor of Chemical Engineering, 1964 to date.

University of Missouri -- Professor and Chairman of Chemical Engineering, 1956-1964.

Iowa State College -- Associate Professor of Chemical Engineering, 1949-1955.

Atomic Energy Commission -- Associate Engineer, Ames Laboratory, Iowa State College, 1950-1955.

Industrial and Government Consulting -- National Research Corp.; Corning Glass Works; National Aeronautics and Space Administration (Greenbelt, Md.); Aircraft Nuclear Propulsion Department of the General Electric Co.

Professional Activities:

Registered Professional Engineer, State of Virginia.

Member of American Institute of Chemical Engineers.

Member of American Society for Engineering Education.

Member of American Chemical Society.

Member of Tau Beta Pi, Sigma Xi and Phi Lambda Upsilon honorary societies.

Recipient of 1970 Wine Faculty Achievement Award for Teaching.

Publications:

Over fifteen articles in the fields of thermodynamic properties measurement, chemical processes and unit operations technology, polymer properties, and metals purification.